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BROAD BEAM ION SOURCE OPERATION WITH FOUR COMMON GASES.(U)

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BROAD BEAM ION SOURCE OPERATION
WITH FOUR COMMON GASES

Technical Report: September 1979

ONR Contract N00014-76-C-0976

Contract Authority NR 243-015

by

Sung-Jae Pak

and

James R. Sites

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Report SF24

Department of Physics

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Broad beam ion source operation for sputtering purposes is shown to be easily convertible from one gas species to another. Krypton requires the least discharge voltage and gives the most efficient beam formation, followed by argon, oxygen, and nitrogen.

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BROAD BEAM ION SOURCE OPERATION
WITH FOUR COMMON GASES

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Fort Collins, CO 80523

ABSTRACT

A Kaufman-type broad beam ion source, used for sputtering and etching purposes, has been operated with Ar, Kr, O_2 and N_2 gas inputs over a wide range of beam energies (200-1200 eV) and gas flow rates (1-10 sccm). The maximum ion beam current density for each gas saturates at about 2.5 mA/cm^2 (sq.cm.) as gas flow is increased. The discharge threshold voltage necessary to produce a beam and the beam efficiency (beam current/molecular current), however, varied considerably. Kr had the lowest threshold and highest efficiency, Ar next, then N_2 and O_2. The ion beam current varied only weakly with beam energy for low gas flow rates, but showed a factor of two increase when the gas flow was higher.

I. INTRODUCTION

Broad beam ion sources, initially developed for space propulsion, have gained increasing success with such industrial applications as pattern etching,[1-5] thinning of materials,[6] sputter deposition,[7-8] and surface texturing.[9-10] In comparison with other techniques, the ion beam offers a high degree of process control, flexibility in target and substrate selection, as well as compatibility with ultra high vacuum.

In most instances broad beam ion systems have utilized argon as a source gas. It is chemically inert, relatively easy to ionize, and reasonably priced. In some applications, however, it is desirable to use other gases. Krypton, for example, with its larger atomic mass, yields a greater amount of momentum transfer when used for sputter etching. Oxygen and nitrogen, though lighter, have proven useful in the reactive sputter deposition of several insulating thin films.[11-14] Other gases, such as CF_4, enhance the sputter etch rate of many materials.[15]

The purpose of the study reported here is to examine the operation of a broad beam ion source, with particular emphasis on comparing the different gases mentioned above. The data reported should be useful for the utilization of these specific gases, and the general trends should allow estimates of expected operation of other gasses or modified source geometries.

II. DESCRIPTION OF ION SOURCE

A schematic drawing of the Kaufman-type ion source used[16] is shown in Fig. 1. Gas enters the cylindrical source chamber through a calibrated leak valve. The source chamber, which is mounted in a high vacuum system, has no unnecessary openings for gas to escape prior to ionization. A discharge is achieved by applying a voltage V_d, the order of 20-50 V, between a hot filament cathode and a cold anode. An array of judiciously placed permanent magnets (~100 Gauss) cause the free electrons to spiral as they approach the anode, thus lengthening their mean free path and increasing their utility for ionization.

The positive ions produced are expelled from the source chamber by maintaining it at a positive potential V_b relative to ground. The energy of the resulting ion beam is determined by V_b and is typically 200-1200 eV. In order to extract a uniform beam, a grid structure is used. The accelerator grid, which is held somewhat below ground potential, has a hexagonal array of 380 small holes. The screen grid, at cathode potential, has a matching array of holes and serves to deflect the ions so they do not impinge on the accelerator grid. In the system studied, the source chamber is about 20 cm in diameter and 10 cm deep. The open grid area is 5 cm in diameter with each individual grid opening about 1.5 mm in diameter.

After the positive ions emerge from the source chamber, electrons emitted from a second hot filament are used to neutralize the beam. The beam then consists of equal numbers of positive ions and negative electrons which do not in general recombine during the times of flight involved. The overall neutrality of the beam, however, achieves two purposes: it minimizes the tendency of the beam to diverge and it eliminates charge buildup on insulating surfaces exposed to the beam. The reason to keep the accelerator grid slightly negative, $\Delta V<0$, is simply to repel electrons from the source and minimize backstreaming effects.

III. RESULTS

When the ion source was operated with argon, krypton, or nitrogen, the beam was quite stable and could be operated continuously for over ten hours. With oxygen, however, the filament lifetimes were somewhat reduced, and they tended to burn out after about two hours. The source was also operated briefly (15 min.) with CF_4. In this case the ionized gas attacked the anode and formed an insulating film which severely restricted the discharge current. Operation with pure H_2 was not successful with the discharge voltage available, although argon-hydrogen mixtures formed very stable beams.

We first measured the effect on the operation of the ion beam system as the rate at which gas is introduced is modified. We chose to express the gas flow rate in ampere equivalent units so that there would be a direct comparison with ion beam currents. An ampere equivalent is simply the molecular flow which would yield a current of 1 A if each molecule were singly ionized. It is equal to 6.25×10^{18} molecules/sec or 13.9 sccm.

The first trend shown in Fig. 2a is that at constant molecular flow, the vacuum chamber pressure, the pressure outside the source chamber, is highest for krypton and progressively decreases for the other gasses. The data is consistant with the pump manufacturer's rating of 1000 ℓ/sec. and a pumping speed roughly proportional to the molecular velocity. The vacuum chamber background pressure is important in sputtering applications because it determines the mean free path of a sputtered atom and hence the deposition rate. Perhaps more important, however, a low background will minimize the possibility of gas from the primary beam being imbedded in the deposited film.

On the other hand, it is seen in Fig. 2b that much less krypton flow is required to sustain a discharge and hence an ion beam. This plot shows the minimum value of V_d, the cathode-anode voltage, necessary to produce any beam at all. This threshold value is always found to be a decreasing function of the gas flow rate. The few data points we were able to take with CF_4 fall slightly above the oxygen data.

Finally, in Fig. 2c, we show the maximum ion beam current, also as a function of flow rate. In each case there is a relatively rapid rise from a minimum required flow rate and then a broad saturation region with currents the order of 50-55 mA ($\sim$2.5 mA/cm^2). The beam efficiency η is found by dividing the beam current by the gas flow rate, assuming that no significant amount of gas reenters the source chamber from the vacuum chamber. Table I shows the maximum value of η for the four gasses used as well as the vacuum chamber pressure at which that maximum occurs.

The relationship between ion beam current and cathode-anode discharge current is shown in Fig. 3. In this case the data is taken at a fixed vacuum chamber pressure (8×10^{-5} torr). Once again we see (Fig. 3a) that the krypton requires substantially less voltage to sustain a discharge, with argon ranking next. At fixed pressure, however, we find that oxygen requires the greatest voltage to maintain the same discharge current. Turning to the beam current produced (with a fixed 800 eV energy) we find that it is roughly the same for all the gases and that it is approximately 1% of the discharge current of electrons. There is a tendency for the oxygen curve to rise above the others at higher discharge currents. We interpret this effect as the dissociation of oxygen molecules into two O^+ ions.

Although the ion beam currents are primarily determined by the gas flow rate, the discharge current, and the type of gas involved, there is some variation due to other parts of the system. Figure 4, for example, shows the dependence on cathode filament current with the other parameters held constant. All the gases exhibit roughly the same curve as that shown for argon. It has a broad maximum, and good operating practice is to stay on the low current side of the maximum ($\sim$17 A) simply so the filament will last longer.

The beam voltage dependence of the ion beam current is illustrated in Fig. 5 for nitrogen. In this case also all the gases were qualitatively the same. For low flow rates (the lowest shown corresponds to a vacuum chamber pressure of 3×10^{-5} torr), the beam current is nearly independent of the source to ground potential. For larger flow, however, the current increases with beam energy by about a factor of two. An alternative way to express the same data is that the saturation of the beam current occurs at higher beam energies when the gas flow rate is greater.

The necessary offset in the accelerator grid voltage relative to ground (ΔV in Fig. 1) is pictured in Fig. 6. In this case the vertical scale is the net positive current flow out of the ion source which includes negative electrons which backstream into the source. The backstreaming is quite apparent for ΔV less than 50 V. in magnitude, the exact threshold varying slightly with the beam voltage, but essentially independent of the gas used. In any case, operation with ΔV near -100 V. prevents the backstreaming problem. The slight rise in beam current as ΔV becomes more negative is thought to be due to a higher probability of extracting ions from the source if the grid-anode potential difference is greater.

IV. CONCLUSIONS

The primary conclusion is that the same broad beam ion source can be used successfully with a number of gases, thus enhancing the flexibility of ion beam sputter etching and deposition processes. It is necessary, however, to be aware of the differences in operating parameters when different gases are used. These parameters may vary from one ion beam system to another, but should follow the general trends reported above.

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Table I. Comparison of Maximum Ion Beam Efficiencies Attained With the Different Gases.

Gas	η [Maximum]	Corresponding Vacuum Chamber Pressure
Kr	40%	5×10^{-5} torr
Ar	25	6.5×10^{-5}
N_2	13	7.5×10^{-5}
O_2	10	10×10^{-5}

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FIGURE CAPTIONS

Figure 1. Schematic of ion beam source.

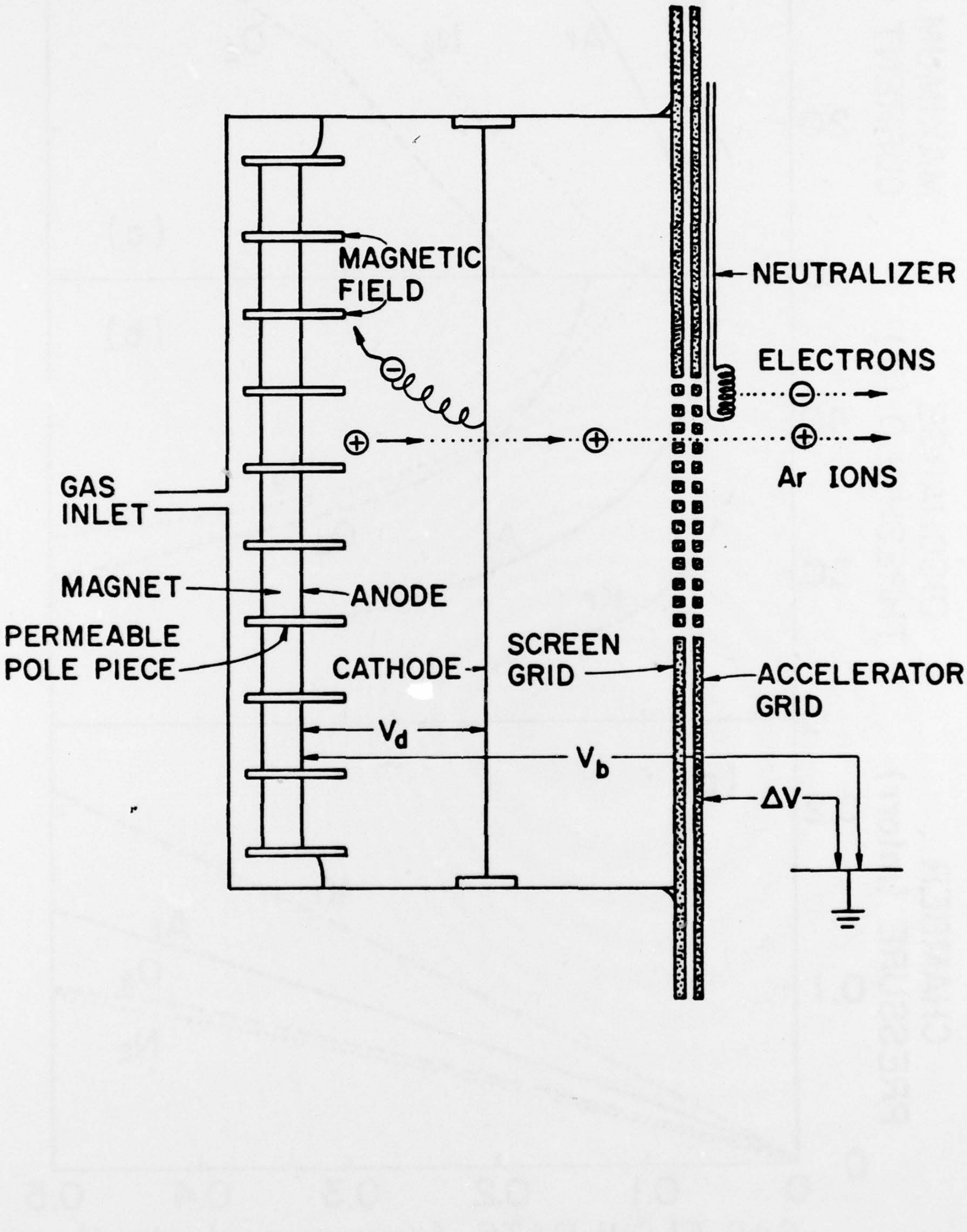
Figure 2. Dependence of (a) vacuum chamber pressure, (b) discharge voltage threshold, and (c) the maximum ion current produced on the gas flow rate.

Figure 3. Relation between (a) the cathode-anode discharge voltage, (b) the ion beam current and the cathode-anode discharge current. Vacuum chamber pressure in each case was 8×10^{-5} torr and beam energy was 800 eV.

Figure 4. Beam current as a function of cathode filament current for argon. Other gases similar.

Figure 5. Beam current as a function of beam energy for nitrogen at different gas flow rates $\dot{Q}$. Other gases similar.

Figure 6. Relation between beam current reading and accelerator grid offset, showing electron backstreaming effect.



MAGNETIC
FIELD
NEUTRALIZER
ELECTRONS
Ar IONS
GAS
INLET
MAGNET
ANODE
PERMEABLE
POLE PIECE
CATHODE
SCREEN
GRID
ACCELERATOR
GRID
V_d
V_b
ΔV

Fig. 1

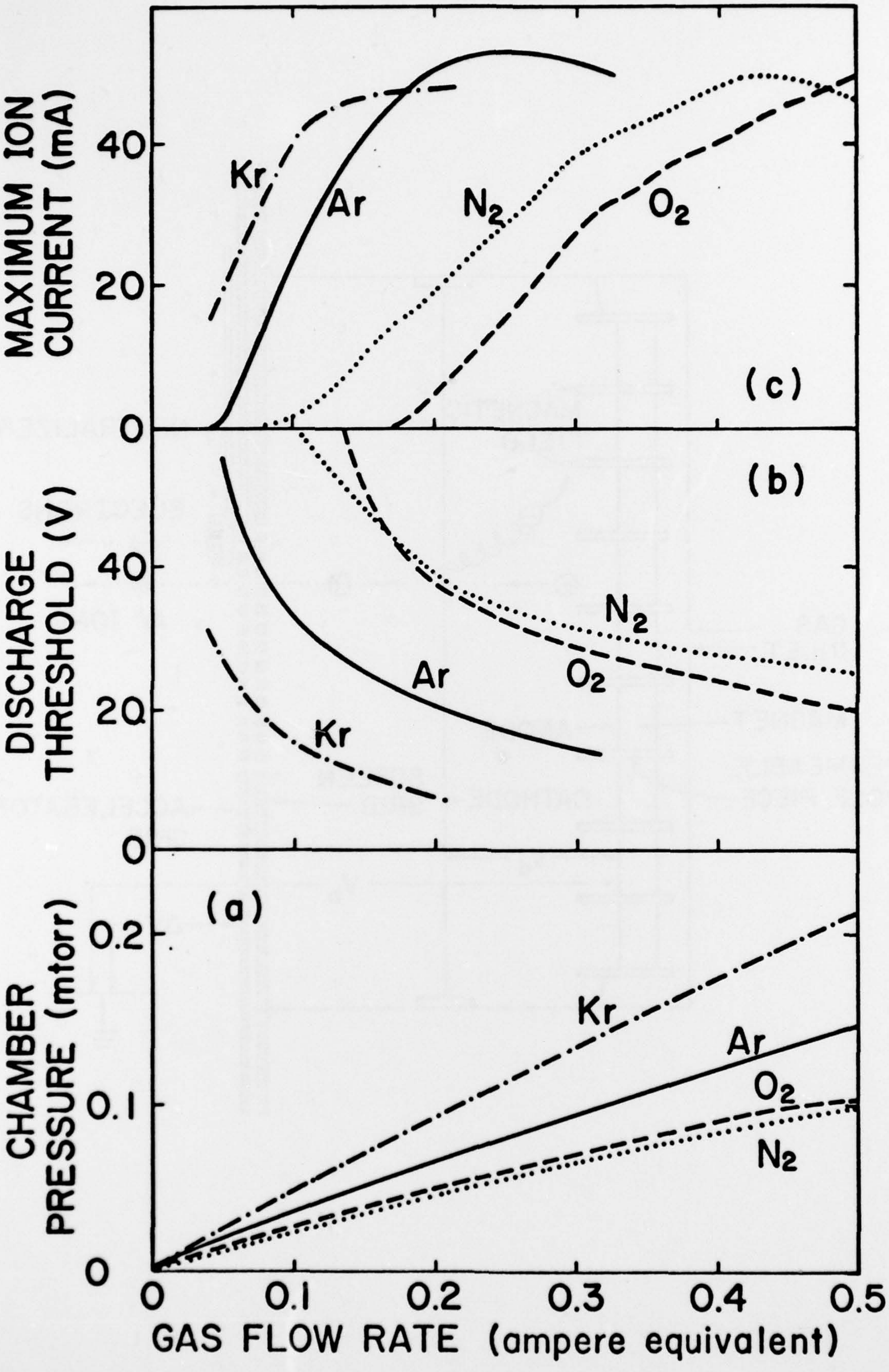
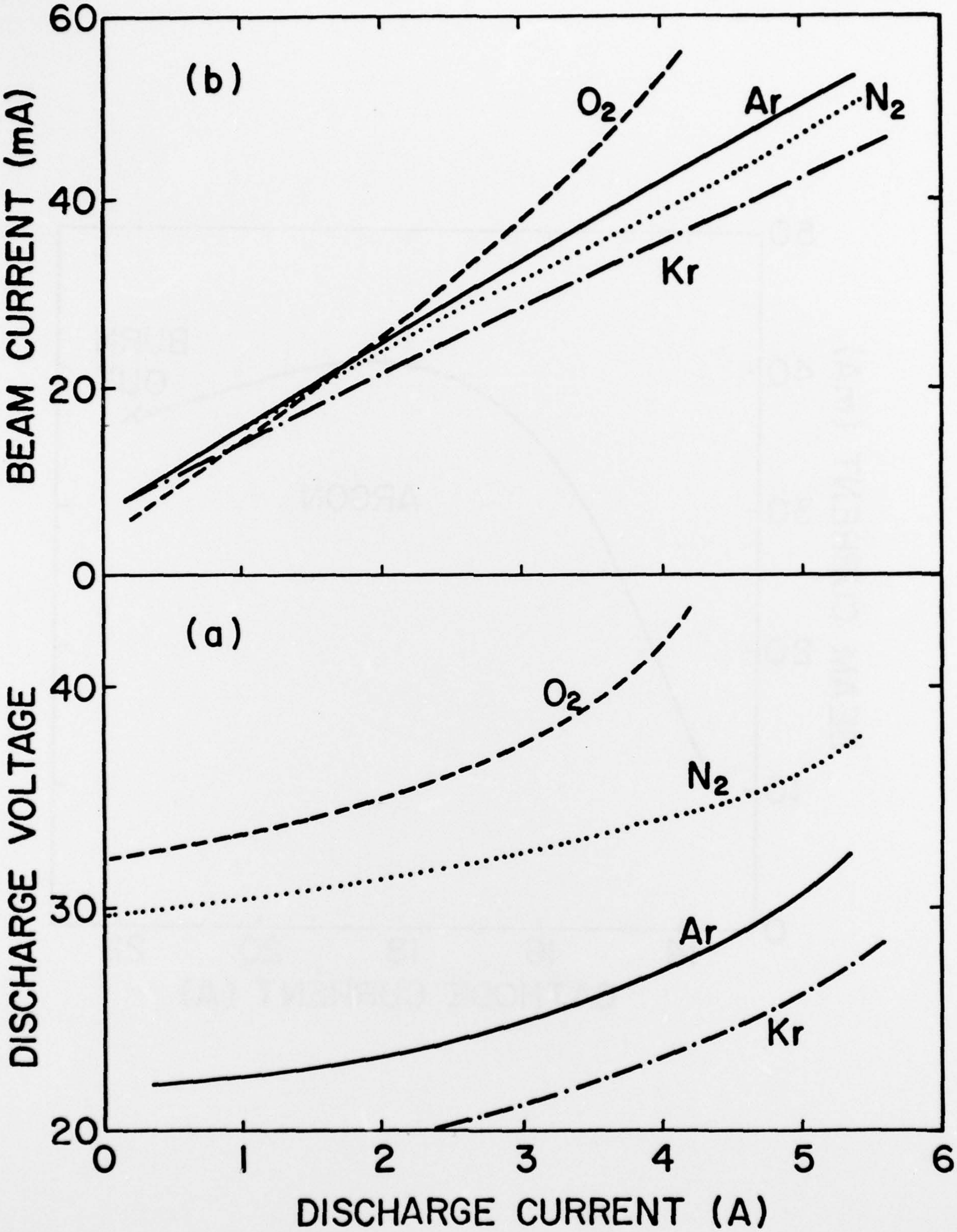

MAXIMUM ION CURRENT (mA)
40
20
0
Kr
Ar
N_2
O_2
(c)
DISCHARGE THRESHOLD (V)
40
20
0
(b)
N_2
Ar
O_2
Kr
CHAMBER PRESSURE (mtorr)
0.2
0.1
0
(a)
Kr
Ar
O_2
N_2
0
0.1
0.2
0.3
0.4
0.5
GAS FLOW RATE (ampere equivalent)

Fig. 2



60
40
20
0
(b)
O2
Ar
N2
Kr
BEAM CURRENT (mA)
(a)
40
30
20
O2
N2
Ar
Kr
DISCHARGE VOLTAGE
0
1
2
3
4
5
6
DISCHARGE CURRENT (A)

Fig. 3

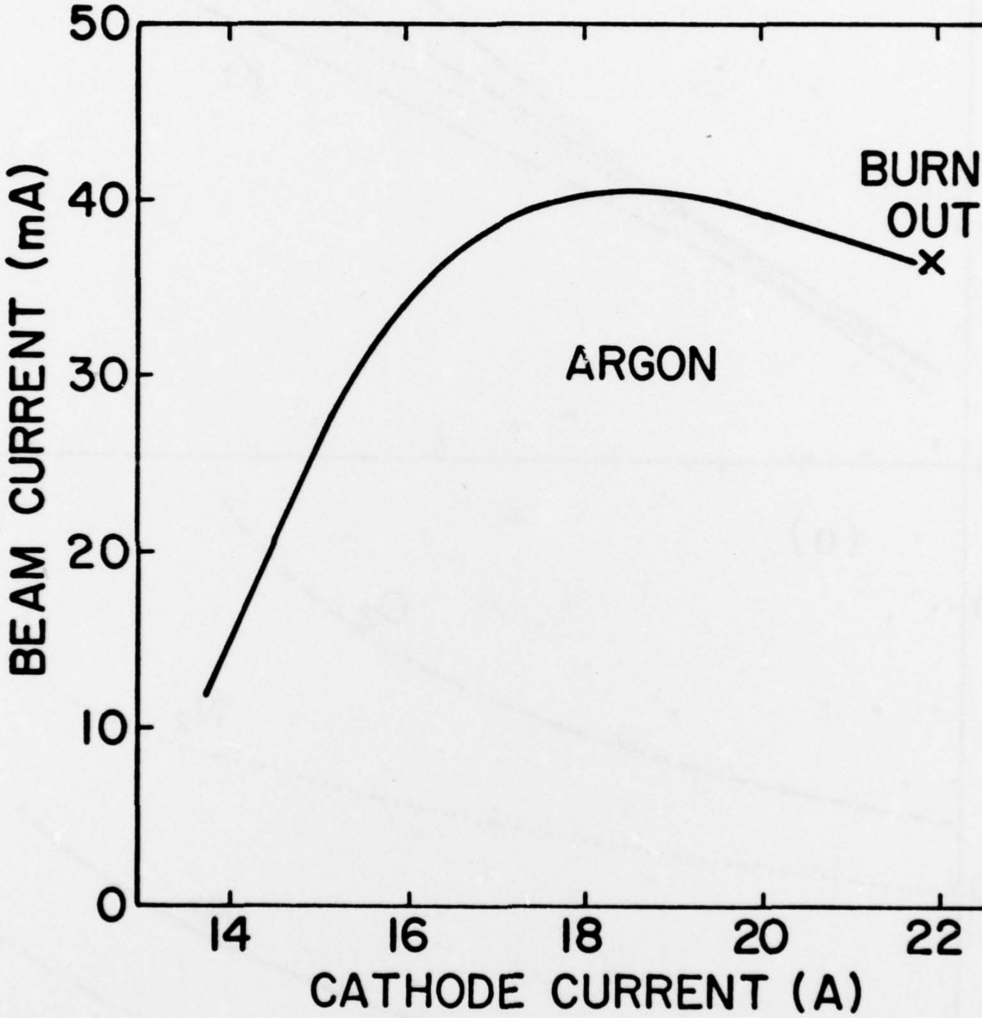
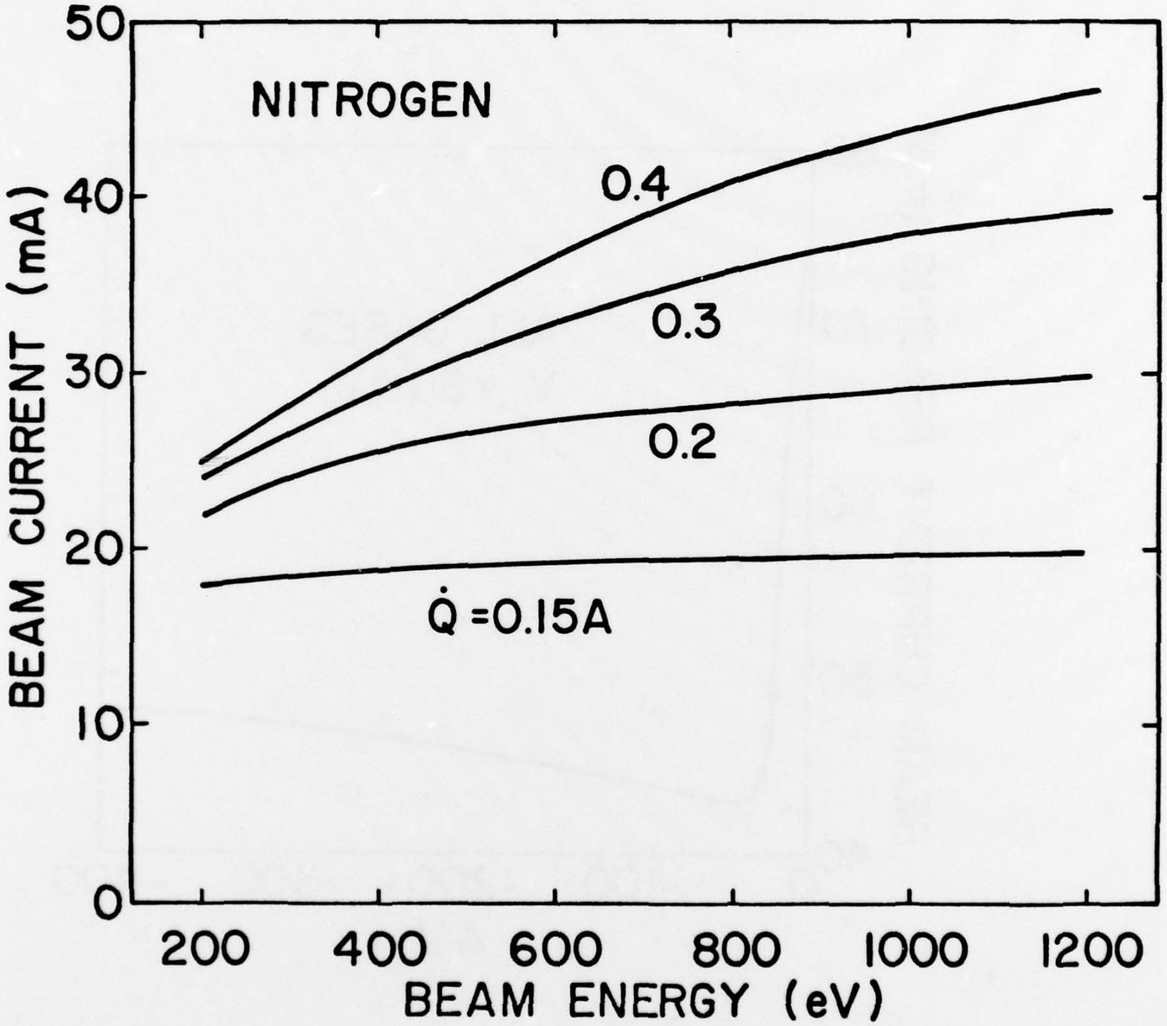

BEAM CURRENT (mA)
50
40
30
20
10
0
14
16
18
20
22
CATHODE CURRENT (A)
ARGON
BURN
OUT

Fig. 4



NITROGEN
0.4
0.3
0.2
$\dot{Q}$ =0.15A
BEAM CURRENT (mA)
BEAM ENERGY (eV)
0
10
20
30
40
50
200
400
600
800
1000
1200

Fig. 5

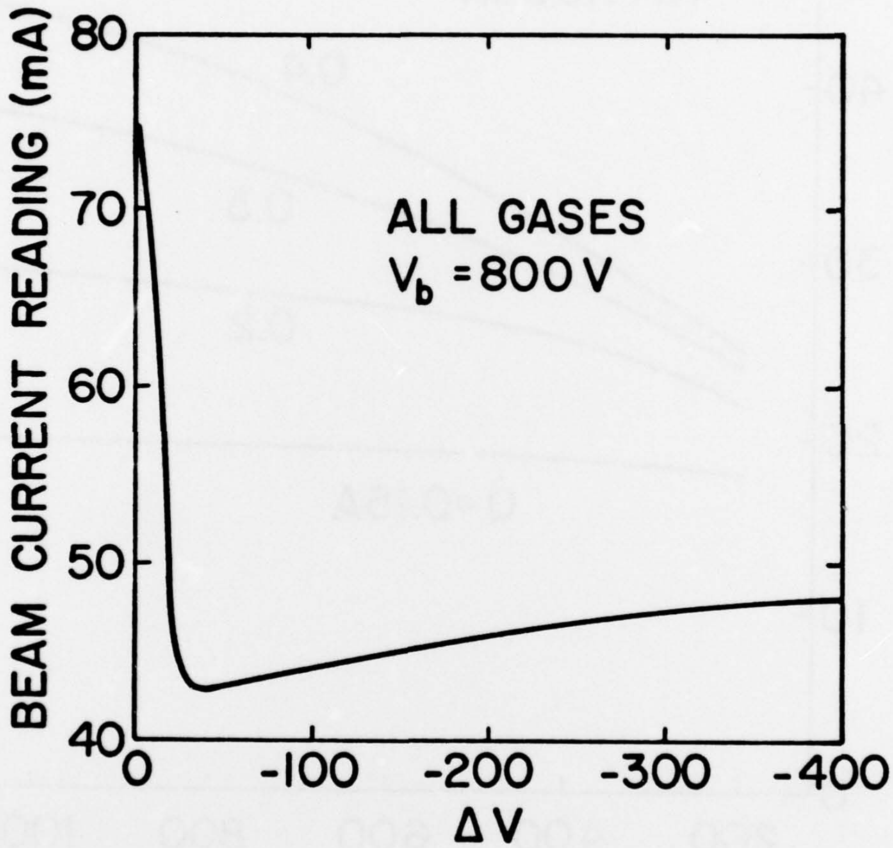

BEAM CURRENT READING (mA)
80
70
60
50
40
0
-100
-200
-300
-400
ΔV
ALL GASES
V_b = 800 V

Fig. 6

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